Journal of Physics: Conference Series **1390** (2019) 012117 doi:10.1088/1742-6596/1390/1/012117

4π semiconductor beta-spectrometer for measurement of ^{144}Ce – ^{144}Pr spectra

S Bakhlanov, A Derbin, I Drachnev, I Kotina, I Lomskaia, V Muratova, N Pilipenko, D Semenov, E Unzhakov

Abstract. Precision measurements of beta-spectra have always been and are still playing an important role in several fundamental physical problems, predominantly in neutrino physics. Magnetic and electrostatic spectrometers possess the superior energy resolution, but at the same time such devices appear to be very complex and large-scale setups. Since the electron free path at 3 MeV (which is, basically, the maximum beta-transition energy for long-living isotopes) does not exceed 2 g/cm^3, solid state scintillation and ionization detectors were effectively employed for detection of electron. In case of semiconductor detectors there is a significant probability of back-scattering from the detector surface that depends on the detector material. This issue could be overcome by constructing a beta-spectrometer with 4π geometry, fully covering the source and capable of detecting backscattered electrons. Here we present a technology allowing production of a beta-spectrometer based on silicon detectors and having 4π geometry. The spectrometer developed had been fitted with a ^{144}Ce-^{144}Pr radioactive source and has demonstrated capability of performing precision beta-spectrometry for this nuclides.

1. Introduction

Since energy nonconservation problem in beta-decay was established by W.Pauli in 1930 [1] and had led to neutrino discovery, beta-spectrometry remains a very important problem for various nuclear and particle physics implications. The beta-decay theory, introduced by E. Fermi shortly afterwards [2] was explaining the main features of the spectral shape, but some decays still can not be described by this theory. For instance, the so-called Fermi Golden Rule is applicable if the beta-process could be described as a single nucleon decay without involvement of the collective motion inside the nucleus. This means parity and momentum limitations for (super-) allowed transitions as $\Delta\pi = +1, \Delta I = 0, 1$. Unfortunately, most of known beta-decays are so-called "forbidden" and their spectral shapes are distorted by internal nuclear collective motion effects; the distortion function is usually referred as the form-factor H(W). As nowadays there is no reliable nuclear model that could be used for the form-factor derivation for most of nuclei, it is unavoidable that this function is obtainable only experimentally. The nuclei studied in this work, ^{144}Ce and ^{144}Pr undergo β- decays with a complex decay scheme, shown on figure1. ^{144}Ce decays with three first forbidden beta-transitions with significant branchings. ^{144}Pr lives only 17.28 minutes and has three beta-transitions with non-negligible branchings, one of them is allowed and goes to 1^- state with excitation energy of 2185 keV, one is first forbidden unique and goes to the 2^+ excited state with energy of 696 keV and the transition with the highest branching ratio of 97.9% goes to the ground state and has the endpoint energy of 2997.44 keV. This source is quite promising for sterile neutrino searches since it is one of the most energetic β^- sources, while inverse beta-decay cross section scales as the square of antineutrino energy.

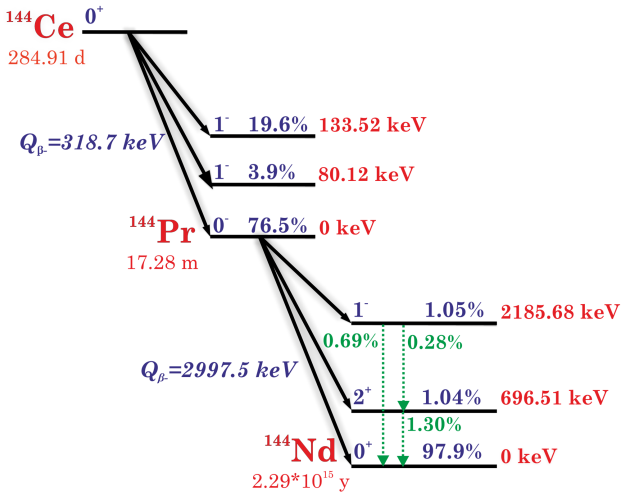

Figure 1. Decay scheme of ^{144}Ce. The scheme shows most intensive beta-transitions of ^{144}Ce and ^{144}Pr that contribute to the detected spectrum. One should notice that all gamma-transitions with energy exceeding 696 keV follow and allowed beta-transition to the 1^- excited state of ^{144}Pr with excitation energy of 2185 keV.

Moreover, since cerium has unique feature of having two possible valencies (3^+ and 4^+), it has additional mechanisms of chemical separation from processed nuclear fuel, that would help in the source preparation. Thus, its precise spectral measurement would play an important role for future sterile neutrino experiments. Unfortunately, the previous studies performed on this beta-spectra form-factors are in disagreement with each other [3, 4, 5, 6, 7] and thus the systematic uncertainty on the spectral shape will severely decrease such experiment sensitivity.

2. Choice of the spectrometric approach

The most traditional approach to beta-spectrometry is usage of various kinds of magnetic and electrostatic spectrometers. These setups have a number of advantages, such as very good energy resolution thanks to zero Fano factor, as well as quite simple detector response. Unfortunately, spectrometers of this kind are quite complex, moreover, their complexity severely increases with electron kinetic energy, limiting availability of this technique for energetic transitions.

Another option is usage of plastic and crystallite scintillators that, as calorimetric detectors, do not have any issues, related with high endpoint energy of praseodymium ground state transition, but have quite poor energy resolution and difficult-to-control systematics due to light quenching effects, Čerenkov radiation and nonuniformity of light collection. Plastic scintillators could also be used with radioactive source chemically binded to the scintillator itself, leaving no issues of the detector light response. Still, the intrinsic problems of this kind of spectrometers limit their maximum achievable precision.

Usage of semiconductor detectors might be a possible compromise since they are calorimetric detectors that have quite good resolution together with a possibility of high-energy electron energy registration. Charge collection of these detectors is significantly more predictable than light collection of scintillators and that makes them able to achieve quite high levels of spectrometry precision. Same time, these detectors have a list of problems, limiting options for their application. First of all, these detectors could be produced in a limited number of shapes, namely they could be made either planar or coaxial. Another problem is the entrance

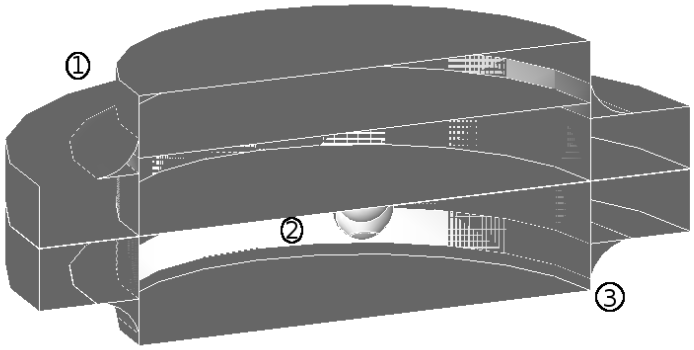

Figure 2. Principal scheme of the beta-spectrometer prototype with 4-π geometry: 1 - upper Si(Li) detector, 3 - lower Si(Li) detector, 2- a drilled hole with the ^{144}Ce – ^{144}Pr beta-source in form of dried solution on the hole surface

window thickness that can not be made negligible in terms of electron energy loss, especially taking into account good energy resolution of these detectors. Also, the detector chemical compound is strictly limited and the source could hardly be implanted into the crystal, thus the only accessible option is usage of the spectrometer with an external source that would suffer from various cases of incomplete electron energy deposition such as entrance window transit,backscattering and bremsstrahlung radiation escape[8]. Here we propose a prototype that is supposed to demonstrate a way out from these limitations making a compact and reliable spectrometer capable of precision beta-spectrometry at high kinetic energies.

3. Experimental setup

4π geometry of the calorimetric spectrometer could bring a number of advantages with respect to simple setup with a source and detector. Namely, a significant fraction of the beta-radiation, falling onto the entrance window of the detector, is backscattered and thus the detector response function differs from a simple Gaussian distribution by a pronounced low-energy tail [8]. Moreover, this tail also includes contributions from bremsstrahlung exit from the crystal, bremsstrahlung from the detector support structure and collimator and detector transit without full energy deposition in case the detector sensitive region in not large enough.

The setup construction is based on the idea of twin planar Si(Li) detector usage [9]. The planar detectors could be attached one to another in reverse order, attaching gold contact of one detector to the gold contact of another detector. The source is located in a hole, drilled in the gold contact surface of one of the detectors, providing enough room for placing of the radioactive source in a form of a dried drop. The offset voltage is applied on both detectors with the common contact with individual charge-sensitive preamplifiers. Thickness of the detectors of the current prototype is 5.5 mm and 4.5 mm. This value is less than the continuous-slowing-down approximation range for 3 MeV electrons, that could be estimated as 7.78 mm [10], so the effect of detector transit without full energy deposition is expected to be significant. The setup is located in a vacuum cryostat and is cooled down to liquid nitrogen temperature in order to decrease the detector current. The setup is also fitted with an external NaI(Tl) gamma-detector, allowing to detect gamma-lines in coincidence with beta-transitions going to excited states of

the daughter nuclei (see figure 2). The signal from charge-sensitive preamplifiers is digitized with 16bit ADC with sampling rate of 250 MHz, that work upon activation of individual digital triggers. The signal from both Si(Li) detectors as well as the scintillating NaI(Tl) detector is digitally shaped with a triangular shaper, allowing to improve signal-to noise ratio with respect to classical quasi-gaussian CR-nRC shapers.

The data are recorded on event basis, allowing to perform offline coincidence analysis. The final spectrum is the spectrum for energy deposition of single detectors in case of no coincidence and the sum of two detectors energy depositions for the case of coincidence, determined through 150 ns temporal window. The energy calibration is performed with ^{207}Bi gamma-lines for both detectors. Thus, the final spectrum shows the total energy deposition in the unification of sensitive volumes of both planar detectors.

4. Data analysis

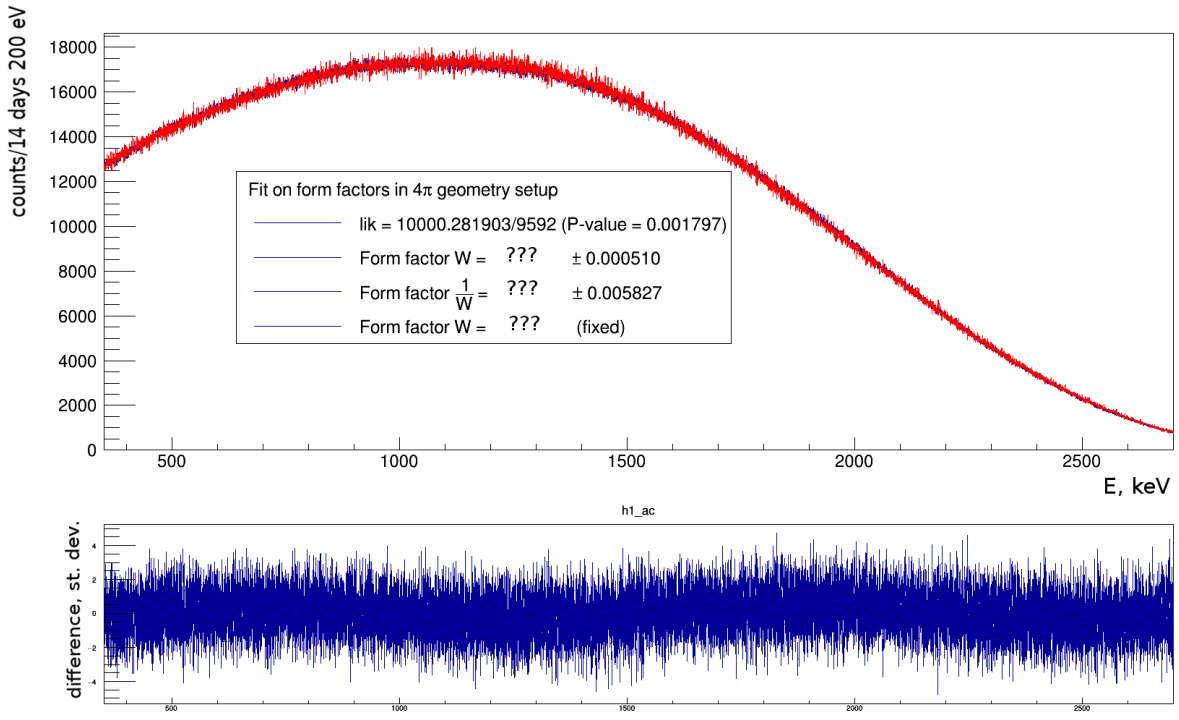

Figure 3. Maximum likelihood fit of the final spectrum of the spectrometer with the ^{144}Ce – ^{144}Pr source . The fit shows satisfactory statistical agreement of the theoretical description with the spectrometer data as well as high sensitivity to the form-factor parameters. The best-fit values are hidden since systematic uncertainties of this preliminary prototype spectrum are not taken under complete control.

The spectrometer response function was derived through Monte-Carlo simulation, performed with Geant4.10.4 simulation package[11]. Electromagnetic physics package used in the simulation was chosen to be G4EmStandardPhysics_option4, that is expected to be the most precise standard package for low-energy physics [12]. Geometry of the setup was measured and reproduced in the simulation with high precision. Sensitive volume thickness, that differs from the detector thickness by a layer of diffusive lithium, unavoidable in Si(Li) detector production technology, was left as two free parameters for both detectors and established via maximum likelihood approach in the final spectrum fitting procedure. Since nuclear form-factor parametrization used gives a limited freedom of spectral shape distortion, while the

distortion caused by the detector transit without full energy deposition has a specific affection on the spectrum, the spectral fit has a sensitivity of order of 0.02 mm for this parameter. Still, simplification of the sensitive region shape to a cylinder contains some difficult to control systematics and thus the future prototypes should have the size that satisfies the condition of no electron escape. The entrance window thicknesses were studied through simulation tuning on gamma and conversion electron peaks of ^{207}Bi and thus the simulation is expected to provide satisfactory precision, especially taking into account that this effect is quite small.

The final spectral fit was performed with maximum likelihood method with standard χ^2 likelihood function. The beta-spectrum was parametrized as

$$S_{beta}(W) = P \times E \times (W - W_0)^2 \times H(W) \times F(W),$$

where P - electron momentum, E - electron kinetic energy, $W = E + m_e c^2$ - total electron energy, W_0 - total endpoint energy, $H(W)$ - nuclear form-factor, parametrized as

$$H(W) = 1 + C_1 \times W + \frac{C_2}{W} + \frac{C_3}{W^2}$$

and $F(W)$ is so-called Fermi function that corresponds to the electromagnetic counterpart, that is computed according to [13, 14] in the following parametrization:

$$F(W) = F_C(Z, E_e)L(Z, E_e)C(Z, E_e)S(Z, E_e)G(Z, E_e)B(Z, E_e),$$

where $F_C(Z, E_e)$ is the coulomb interaction between the electron and the point-like nuclei, $L(Z, E_e)$ is the electromagnetic finite-size correction, $C(Z, E_e)$ is weak finite-size correction, $S(Z, E_e)$ is screening correction, $G(Z, E_e)$ is radiative correction and $B(Z, E_e)$ is weak magnetism correction. These functions were computed according to [13, 14, 15, 16, 17, 18] The total fit function has the following form:

$$f(E) = \sum_{\beta} S(E) \circledast F_e(E, \tilde{E}) + S_{conv.}(E) + S_{\gamma}(E) + S_{^{154}Eu}(E) + S_{^{244}Cm}(E) + S_{^{241}Am}(E),$$

where the sum is performed for all beta-transitions, $F_e(E, \tilde{E})$ is the spectrometer response function, obtained with Monte-Carlo method spectrometer simulation, $S_{conv.}(E)$, $S_{\gamma}(E)$, $S_{^{154}Eu}(E)$, $S_{^{244}Cm}(E)$ and $S_{^{241}Am}(E)$ are spectral shapes of contributions from conversion electrons and gamma-radiation due to deexcitation of excited states of ^{144}Ce and ^{144}Pr and source contamination with ^{154}Eu, ^{244}Cm and ^{241}Am respectively. These spectral shapes are derived through a Monte-Carlo simulation with uniform contamination of the initial radiation source inside the cerium target.

The fit shows satisfactory agreement with the obtained spectrum taking into account that the form-factor model is empirical and should not describe the spectral shape precisely, see figure3.

5. Conclusions

A beta-spectrometer prototype with Si(Li) detectors and 4π geometry was constructed. The setup shows good spectral resolution and allows to perform beta-spectrometry in a broad energy range, reaching endpoint energy of ^{144}Pr, that is basically the highest energy for beta-decaying nuclides. The setup response could be described with the current standard physical models of Geant4 package, providing good statistical agreement of the model with experimental data. The current prototype still has some issues in the response description due to difficult to control systematic effects, but the future implementations of the current strategy would allow high-precision spectrometry for ^{144}Pr beta-decay energy. This work was supported by Russian Science Foundation, RSF 17-12-01009.

References

[1] Pauli W 1930 Open letter to the group of radioactives at the gauverein meeting in tübingen *Preprint* http://cds.cern.ch/record/83282/
[2] Fermi E 1934 *Zeitschrift für Physik* **88**(3) 161–77
[3] Graham R L, Geiger J S and Eastwood T A 1958 *Canadian Journal of Physics* **36** 1084–111 *Preprint* `https://doi.org/10.1139/p58-115`
[4] Daniel H and Kaschl G 1966 *Nuclear Physics* **76** 97 – 117
[5] Laubitz M J 1956 *Proceedings of the Physical Society. Section A* **69** 789
[6] Nagarajan T, Ravindranath M and Venkata Reddy K 1971 *Il Nuovo Cimento A (1965-1970)* **3** 699–708
[7] Bosch H E, Behar M, Cambiaggio M C, Bermudez G G and Szybisz L 1973 *Canadian Journal of Physics* **51** 2260–69
[8] Alexeev I, Bakhlanov S, Bazlov N, Chmel E, Derbin A, Drachnev I, Kotina I, Muratova V, Pilipenko N, Semyonov D, Unzhakov E and Yeremin V 2018 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **890** 64 – 67
[9] Derbin A, Egorov A I, Mitropolskii I, Muratova V N, Bakhlanov S, and Tukhkonen L 1997 *JETP Lett.* **65**
[10] Berger M and et al J C 2017 Stopping-Power & Range Tables for Electrons, Protons, and Helium Ions
[11] Agostinelli S, Allison J, Amako K, Apostolakis J, Araujo H, Arce P, Asai M, Axen D, S and et al 2003 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **506** 250 – 303
[12] Bagulya A, Brown J M C, Burkhardt H, Grichine V, Guatelli S, Incerti S, Ivanchenko V N, Kadri O, Karamitros M, Maire M, Mashtakov K, Novak M, Pandola L, Rancoita P G, Sawkey D, Tacconi M and Urban L 2017 *Journal of Physics: Conference Series* **898** 042032
[13] Huber P 2011 *Phys. Rev. C* **84**(2) 024617
[14] Hayen L, Severijns N, Bodek K, Rozpedzik D and Mougeot X 2018 *Rev. Mod. Phys.* **90**(1) 015008
[15] Buhring W 1984 *Nuclear Physics A* **430** 1 – 20
[16] Sirlin A 2011 *Phys. Rev. D* **84**(1) 014021
[17] Wilkinson D 1989 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **275** 378 – 86
[18] Wilkinson D 1990 *Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment* **290** 509 – 15